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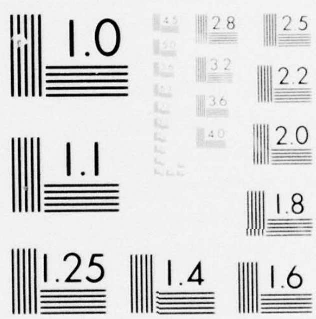

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A NEW CONCEPT IN SLUDGE FILTRATION THEORY FOR AIR FORCE INDUSTRIAL PROCESSESS

DET 1 HQ ADTC/ECW
TYNDALL AFB FL 32403

31 DECEMBER 1976

CEEDO

FINAL REPORT FOR PERIOD 1 JAN 1974 TO 30 JUN 1974

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CIVIL AND ENVIRONMENTAL ENGINEERING DEVELOPMENT OFFICE
(AIR FORCE SYSTEMS COMMAND)
TYNDALL AIR FORCE BASE
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The specific objective of this investigation was to apply existing theoretical concepts used in air filtration to various sludge filtration systems used in Air Force industrial processes. This objective involved development of a consistent theoretical concept applicable to a wide range of water filtration systems. Once developed, these equations were used to describe the sludge filtration process of concern to the Air Force as a

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20. ABSTRACT (continued) ef p1473A)

function of the basic system parameters rather than using the classical empirical data base.

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PREFACE

This report summarizes work done between 1 January 1974 and 30 June 1974. Stephen P. Shelton, Capt, USAF, BSC, was the project engineer; however, the work was performed while Capt Shelton was a PhD candidate at the University of Tennessee, Knoxville, as part of a university-sponsored research and development project.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.

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Director of Environics

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Commander

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SECTION I

INTRODUCTION

The United States Air Force operates a diverse group of industrial processes, many of which create liquid wastes. One of the by-products of the treatment of liquid wastes is sludge - a viscous slurry of solids suspended in water or other supporting medium. One of the foremost methods of sludge disposal is filtration. This process yields a more easily handled solid waste which can be dried or, in some instances, reused in the industrial process.

Because the Air Force operates industrial processes throughout the world in diverse climates, standard empirical methods of sludge filtration do not offer the data base to yield successful design under all circumstances. This problem, therefore, indicates a need for theoretical approach to sludge filter design that considers the basic system variables and does not rely greatly upon any empirical data base. This investigator has previously developed some theoretical concepts in aerosol mechanics that should apply to the design of sludge filtration systems in the broad base; therefore, the specific objective of this investigation was to apply these existing theoretical concepts used in aerosol mechanics to sludge filtration. This objective involved development of a consistent theoretical concept applicable to a wide range of water filtration systems; however, primary interest was focused upon vacuum filters. A quantitative model was formulated to describe the sludge filtration processes as a function of the characteristics of the fluid, suspended particles and filter media.

SECTION II

SLUDGE FILTRATION THEORY

Vacuum filtration is potentially the most universal method of sludge dewatering by mechanical means in the Air Force. A uniformly dewatered sludge cake can be produced from either raw or digested sludge. Vacuum filter performance is classically measured in terms of the yield of solids, on a dry weight basis, expressed as mass per unit area per hour. The quality of the sludge filter cake is described by its moisture content on a wet weight basis expressed as a percent of the mass of dry solids. As discussed by Gale (Reference 1), present theory falls short of complete description of the sludge filtration process. However, the theory does illustrate how sludge filterability data can be obtained and how operational variables may affect filter performance.

From the Carman-Kozeny (References 2 and 3) equation the headloss, caused by a given face velocity through a filter cake of given thickness and porosity, can be determined with empirical coefficients for filter resistance and sludge particle characteristics. For convenience in the characterization of sludge filterability, the properties of the sludge and the media are combined into a single specific resistance parameter, r. When this is done, the sludge filtrate volume may be expressed as a function of time:

$$\frac{dV}{DT} = \frac{P_t A_u^2}{(r_c \mu_g W_c + r_f \mu_g A_u)} \qquad (1)$$

where dV/dt is the change in filtrate volume, V, with respect to time, t; P_t is the total pressure drop across the filter; A_u is the unit area of filter; r_c and r_f are the specific resistances for the sludge particle take and the filter cloth, respectively; W is the dry weight of the unit area filter cake; and μ_g is the dynamic viscosity of the fluid.

Equation 1 is commonly integrated to provide a mathematical model for analysis of filtration data to permit determination of r_c and r_f; however, Gale (Reference 1)

has pointed out that, with compressible sludges this procedure is invalid. This is because an increasingly greater percent of the total pressure drop occurs across the filter cake as filtration progresses and the cake increases in thickness. If the cake is compressible, the increasing pressure will cause an increased specific resistance. Hence, r_c increases with time and Equation 1 cannot be integrated.

Gale (Reference 1) also noted that in the advanced stages of filtration, nearly all of the pressure drop can be attributed to the cake while the filter cloth resistance becomes negligible. Under these circumstances the pressure gradient across the cake, and thus the specific resistance, may be considered constant. Thus, if the initial surge of filtrate is ignored, r may be set equal to zero and Equation 1 may be integrated to yield:

$$\frac{t}{V} = \left[\frac{\mu_g W_c r_c}{2\ P_t A_u^2}\right] V \qquad (2)$$

where t/V is the time per unit volume of filtrate. This equation provides a means to evaluate the filterability of a sludge using data on filtrate volume after the initial surge. Specific resistance can be determined from the slope (the terms in brackets in Equation 2 equal the slope) of a plot of t/v as a function of V.

Because many sludges encountered in wastewater treatment are compressible (References 1, 3, 4, and 5), the specific resistance of the sludge cake is influenced by the pressure differential across the cake. Empirically (References 1 and 4), it has been found that specific resistance can be predicted:

$$r_c = r'_c \ P_t^{\ s} \qquad (3)$$

where r_c is the specific resistance r'_c is the precompression specific resistance, P is the total pressure across the system, and s is the coefficient of compressibility measured empirically (when s equals zero, the cake is incompressible and r is independent of pressure). If Equation 3 is rewritten:

$$\ln r = \ln r \ + s \ln \ P \qquad (4)$$

and a log-log plot of specific resistance, r_c, versus total pressure drop, ΔP_t, the coefficient of compressibility, s, is the slope and the precompression specific resistance, r , is at the $\Delta P_t = 1$ intercept.

Using the above discussed equations, the specific resistance and compressibility coefficient of a sludge may be estimated in the laboratory. This is normally accomplished using a Buchner funnel (References 1 and 4) and filter paper by measuring the cumulative filtrate volume as a function of time when the sludge is dewatered by the apparatus at a known pressure differential.

While the sludge filtration theory described in the preceding paragraphs is defined to some degree, it has found little application in the form presented. The filter leaf test is preferred by designers because a variety of pressures, cycle times, and filter cloths can be evaluated readily. In addition, design information and plant operating data have been shown to yield reasonably compatible data for a number of different cases (Reference 5). The filter leaf can be used for determination of specific resistance compressibility coefficients in place of the Buchner funnel if care is exercised in the maintenance of the chronological filtrate volume data.

Many derivatives of the basic filtration equation exist, but most are valid only under restricted conditions in sludge filtration. Specifically, the often used expressions that incorporate cake and fabric at a constant pressure differential across the system are invalid for compressible cakes. Numerical integration of this expression is needed to obtain valid theoretical solutions. An appreciation of the physical mechanism involved in sludge flow, cake formation, and compression is necessary to determine the suitable relationships to be applied so that valid pressure, flow, and time relationships may be determined.

This section has examined the existing theories and empirical methods used in the design and application of vacuum filtration systems. It was shown that most previous research has been primarily interested in the hydraulics of the fluid within the media. The characteristics of the particles, suspended in the fluid, have received some attention; however, the methods used to describe the effect of these particles upon flow, pressure, and time have been semi-quantitative or empirical.

For this reason, subsequent sections will develop the concept of filtration performance including consideration of the characteristics of the suspended particles in the fluid. Since small particle technology, developed primarily in aerosol mechanics, has permitted air filtration theory to consider suspended particle characteristics, it seems likely that these concepts could well be a useful tool in the conceptual development of vacuum filtration models.

SECTION III

PROPOSED VACUUM FILTRATION MODEL

The model to design vacuum filtration systems, proposed by this investigation, requires data that describes the sludge, the filter, and the operating conditions. With these data, the relationship between flow, time, pressure drop and efficiency can be evaluated. The specific information that must be defined for the model includes total pressure difference maintained across the filter, cycle time, integration increment, sludge temperature, fluid density and dynamic viscosity. Information required for the adequate statistical description of the sludge particles includes concentration, mass mean particle size, log-normal standard deviation of particle size, density of the discrete sludge particles and bulk density of the particle cake before compression. In addition, if the sludge cake is compressible, coefficients for the Huffine and Bonilla (Reference 4) compressibility equation are required to determine the effect of cake compression upon filtration rate.

The information required to determine the statistical characteristics of the filter cloth includes the mass mean fiber diameter, log-normal standard deviation in fiber size, fabric thickness, fabric bulk density and the continuous density of the material from which the fibers are made.

With these input data, the model characterizes the systems and begins to calculate the incremental relationship between flow, time, pressure and efficiency. Cake compression, if it occurs, is considered by application of the Huffine-Bonilla equation. This empirical relationship determines the rate of change in the bulk density as a function of applied pressure and empirical coefficients for the sludge under consideration. The rate of cake compression is determined by compression testing in the sludge of concern.

SECTION IV

MODEL SENSITIVITY AND DATA EVALUATION

The model developed for sludge filtration considers the change in filtration velocity at constant pressure across the filter system. In addition, the model can consider cake compression by expression of cake thickness and bulk density as a pressure dependent function. This consideration may be necessary for certain filter systems that operate at a high differential pressure that is sufficient to cause compression in the filter cake.

With respect to the parameter study of the new sludge filtration model, it seems pertinent to point out that the cake thickness value, predicted by the model, is the form thickness and not the thickness after air-suction drying. The dried cake thickness is most often reported in the literature since it is the final product of vacuum filtration. The best function of the sludge model presented herein, therefore, is for prediction of sludge filterability from a basic consideration of the characteristics of the sludge particles. The model allows comparison of different cycle time and pressure differentials to maximize process efficiency. From these data the best filter can be subsequently designed.

Figure 1 shows the effect of particle size upon the relationship between cake thickness and time for a defined sludge. Note that, for these representative data, cake thickness is inversely proportional to sludge particle size. Figure 1 also indicates that larger mass-mean sludge particles tend to increase the slope of the cake thickness as a function of time curves. This trend is a manifestation of the increased interception parameter and a decreased diffusion parameter. Secondary influence on this trend, exerted by the increase in particle size, is found in the filter drag term where the surface-to-volume ratio variable decreases as particle size increases; hence, the net drag is reduced. This is very likely a factor in the difference in filterability of raw and digested sludge. During sludge digestion, particles tend to agglomerate and thus the massmean particle size increases. If the digested sludge is elutriated, the fine sludge particles are washed away; this further increases the mass-mean particle size. Thus, the model would predict that a digested elutriated sludge would be more amenable to filtration than would a raw sludge; this prediction is normally true in sludge filtration.

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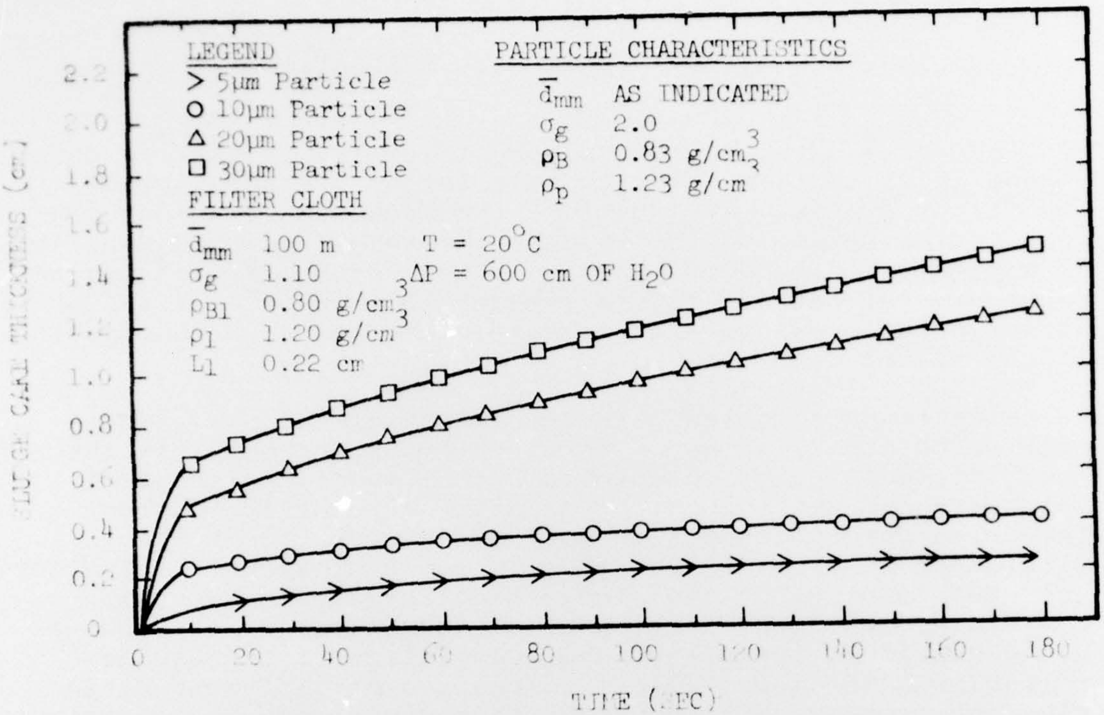

Figure 1. Sludge Cake Thickness
as a Function of Time for 5μm, 10μm, 20μm
and 30μm Mass Mean Diameter Sludge Particles

The preceding discussion has described the trends in Figure 1 in qualitative terms. If the data in Figure 1 were evaluated quantitatively for a real sludge, a decision function could be developed that would trade off filtration time (i.e., drum speed in a vacuum filter) with particle size, equipment cost, and power cost. One consideration would involve increased drum speed for small particles since the greatest portion of the cake forms rapidly and little additional thickness is gained by extended filtration time. Conversely, a slow drum speed would be advantageous for large particles since they tend to yield substantial cake thickness increased after the initial surge. Thus, here again, the effect of the particles suspended in the fluid are predicted to be very influential upon the characteristics of the filter design and operation.

Figure 2 predicts the relationship between sludge cake thickness and system pressure drop. This figure indicates the similar concepts to those indicated by Figure 1; however,

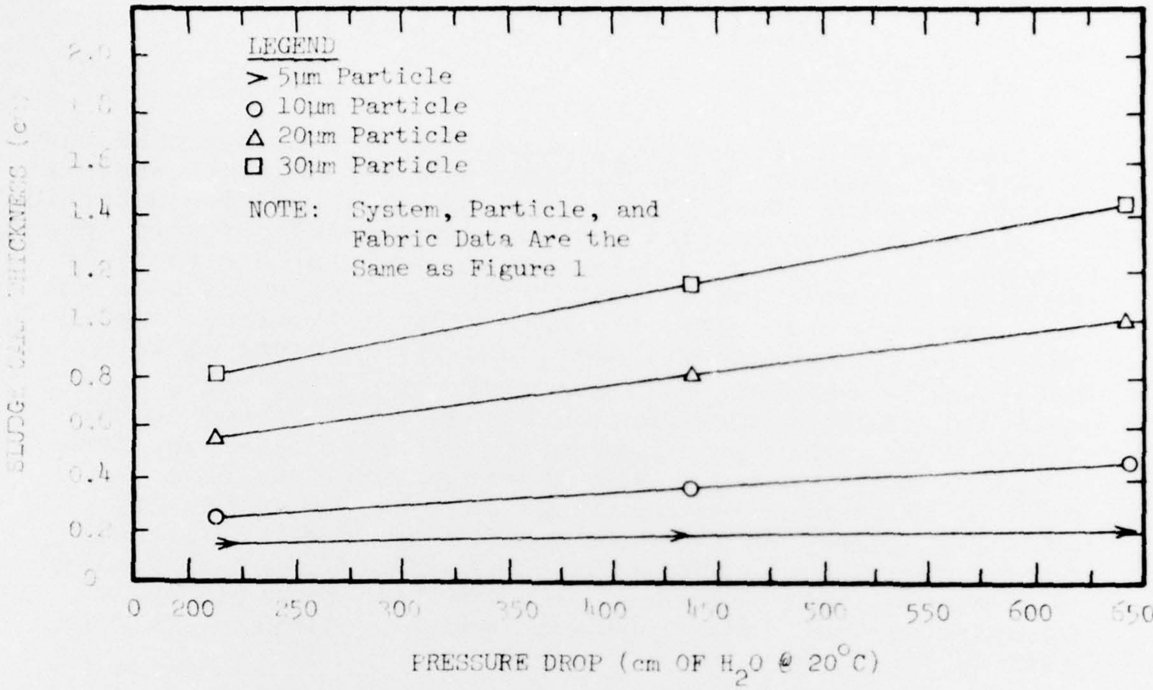

Figure 2. Sludge Cake Thickness as a Function of Pressure Drop for 5µm, 10µm, 20µm and 30µm Mass Mean Diameter Sludge Particles

the large particle filterability is more clearly shown when related to pressure drop. Specifically, the figure indicates that a 200 percent increase in pressure differential yields only 0.1 cm increase in cake thickness for a 5.0µm mass-mean particle size while the same increase in pressure yields a 0.7 cm increase in cake thickness for the 30.0µm mass-mean particle size. Furthermore, at the same pressure, the 30.0µm mass-mean particle cake thickness ranges from 578 percent to 626 percent thicker than the 5.0µm mass-mean particle cake from low to high pressure differential. This indicates again the great influence upon filterability of the mass-mean particle size of the sludge suspension.

Since the literature data does not normally measure the form thickness of the sludge cake, sludge filtration experiments were designed to evaluate the parameters required for limited model verification. These experimental investigations characterized the operation of the fullscale vacuum filters at the two wastewater treatment plants and subsequent laboratory filter leaf tests were run to complement field tests.

The field tests involved measurement of sludge cake form thickness, pressure drop, filtration time, and unit area sludge cake dry mass. Laboratory analysis included determination of sludge characteristics including suspended particle concentration in the sludge and average discrete sludge particle density. In addition laboratory sludge leaf tests were run and cake form thickness, pressure drop, filtration time, unit area sludge cake dry mass, and filtrate volume were measured. From these data two types of filter cakes were observed. Wastewater treatment plant No. 1 proved to have sludge that formed an incompressible filter cake over the pressure range tested. This characteristic was observed both in full-scale vacuum filter data and in laboratory data. At pressures in excess of 500 cm of water further compression was not observed. These data were both applied to a plot of cake thickness as a function of differential pressure so that comparison with model prediction could be made.

Figure 3 is a plot of observed data and predicted relationships by the filtration model. Note in the figure that the laboratory data and field data are not equivalent. This disparity is attributed to the accuracy of the pressure

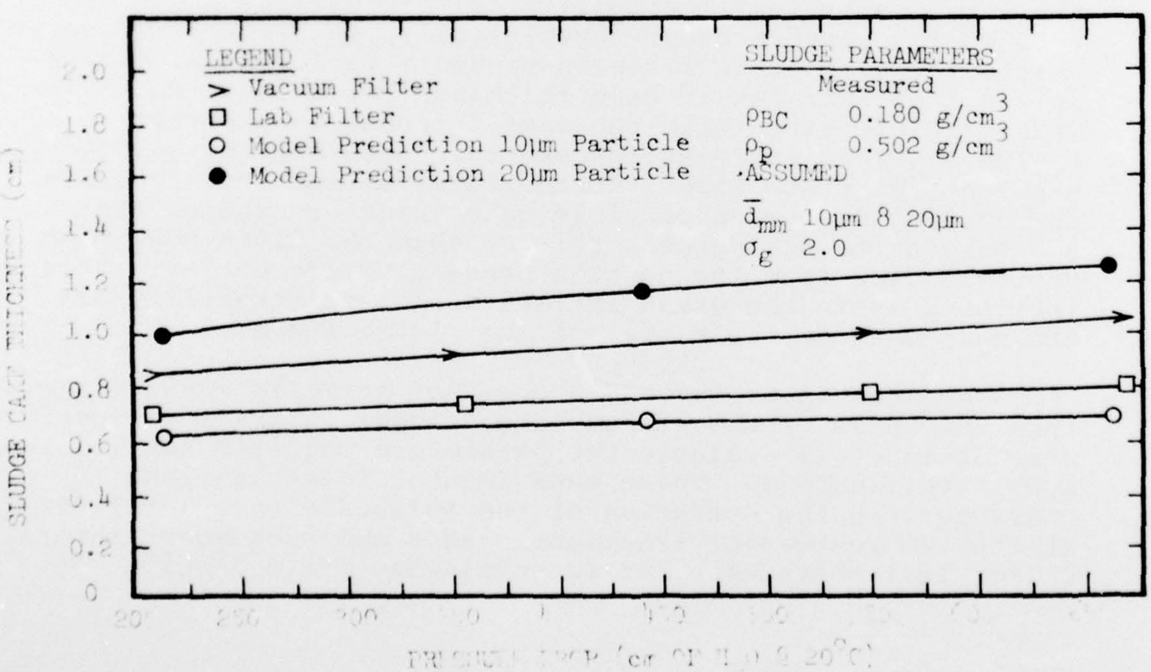

Figure 3. Sludge Cake Thickness as a Function of Pressure Drop for Field Data and Model Predictions From Wastewater Treatment Plant No. 1.

measurement in the field and to subtle modifications in sludge characteristics that may have occurred between field and laboratory testing. Even with these differences, the curves are of similar shape, are reasonably parallel to each other, and are probably within the accuracy of the field measurement techniques used. Application of the sludge filtration model was accomplished by assuming that mass-mean particle size ranged between 10μm and 20μm; this is within reported values in the literature (References 6 and 7). In addition, a log-normal standard deviation of 2.0 was assumed for the sludge particle size distribution; this too has been reported to be a typical value for sludge suspensions (Reference 8). With these assumptions, with respect to sludge particle characteristics, distribution, and the measurement of other parameters required for model input, the two data curves were bracketed by the model predictions. Furthermore, the two particle sizes evaluated by the model yielded curves of the same general shape and slope as the measured data curves.

The information displayed in Figure 3 seems to substantiate that the sludge filtration model has merit. The true ability of this model to evaluate sludge filtration, however, requires a more extensive experimental investigation so that particle size and distribution can be characterized. In addition, like any model, the true validity is ascertained only after widespread application to a diverse sampling of sludge filtration systems. It seems, however, that the relationships developed and the validity obtained from the preliminary field data is sufficient to warrant further work to evaluate more fully the character and accuracy of the model.

As mentioned, the sludge taken from wastewater treatment plant No. 2 formed a compressible cake. To evaluate these data with the sludge filtration model, it was necessary to apply the correction factors for cake compression. The data and model predictions for wastewater treatment plant No. 2 sludge are presented in Figure 4. The curves indicate that the initial linear region of sludge compression is very short. This is followed by a reasonably wide compression range (observed between approximately 175 and 500 cm H_2O at 20°C), after which maximum bulk density occurs and further compression is not observed. There are several ways to evaluate what is actually occurring by comparison with Figure 3. It is likely that the pressure required to form the sludge cake matrix at wastewater treatment plant No. 1 is lower; thus, maximum bulk density has occurred at a pressure of approximately 175 cm of water (at 20°C). If

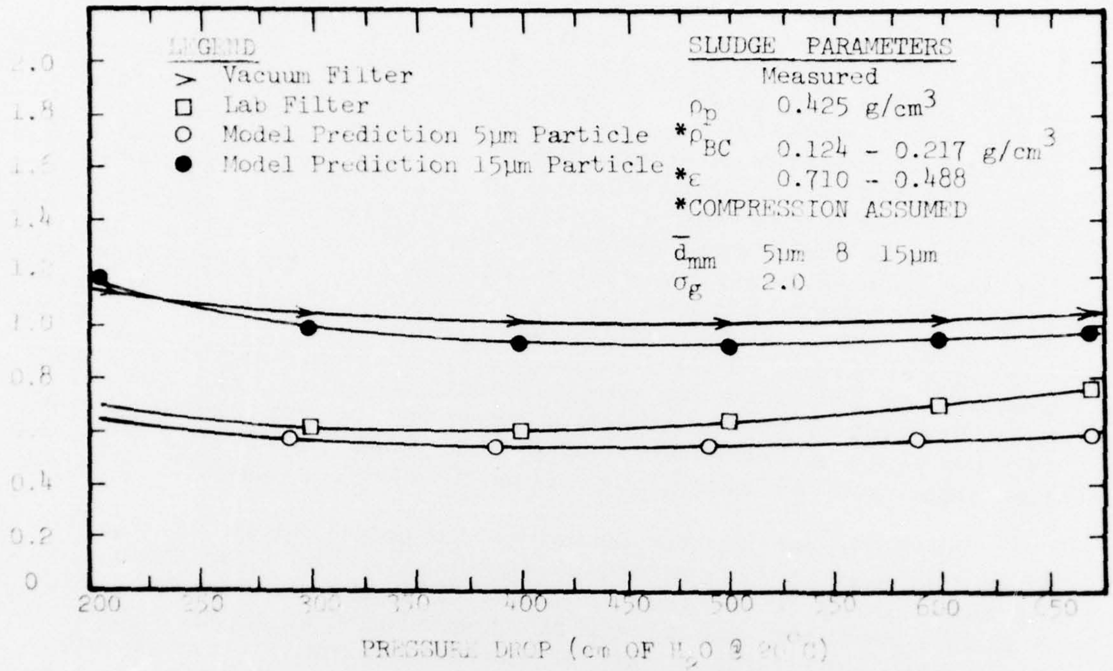

Figure 4. Sludge Cake Thickness as a Function of Pressure Drop for Field Data and Model Predictions from Wastewater Treatment Plant 2

this is the case, the pressure required to form the sludge cake matrix at wastewater treatment plant No. 2 may be higher, approximately 500 cm of water (at 20°C), and thus the previously mentioned linear precompression portion of the curve exists only instantaneously. Either case would, however, not affect the model performance for prediction since the required inputs are empirical and the maximum bulk density must be experimentally determined.

It is felt that the previous comments, with respect to model applicability, were generally applicable to Figure 4. It is also thought that predictions of the effect of cake compression made by the Huffine and Bonilla equation (4) are reasonably valid; however, it should be recognized that the method of presentation of the data in Figure 4 could be considered biased since the observed compression coefficients were used to evaluate the equation. For this reason the sludge model is, to some degree, empirically fit to the data with which it is being compared.

SECTION V

CONCLUSIONS

The new concepts developed for application to sludge filtration performed well in the parameter study. This indicated that the sludge particles and their concentration are very influential upon their filtration characteristics. When the model was applied to preliminary experimental data, it was found to agree well with these data. This application included prediction of the relationship between pressure drop and cake thickness for incompressible and compressible filter. It is felt that the sludge filtration model, developed from aerosol mechanics theory and modified for water application, has been proven to adequately predict the relationships between flow, time, pressure, and efficiency for the cases discussed. It appears, though only preliminary data have been evaluated, that the model is sufficiently promising to warrant future experimental research.

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